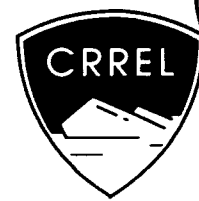


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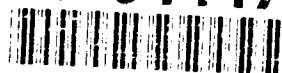
Low-Temperature Effects on the Design and Performance of Composting of Explosives-Contaminated Soils

Olufemi A. Ayorinde and Charles M. Reynolds

March 1991



91-01117



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

*COVER: Compost pile in enclosure at the
Badger Army Ammunition Plant
in Baraboo, Wisconsin.*



**U.S. Army Corps
of Engineers**
Cold Regions Research &
Engineering Laboratory

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Prepared for
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY

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PREFACE

This report was prepared by Dr. Olufemi A. Ayorinde and Dr. Charles M. Reynolds, Research Physical Scientists, of the Geochemical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL).

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Low-Temperature Effects on the Design and Performance of Composting of Explosives-Contaminated Soils

OLUFEMI A. AYORINDE AND CHARLES M. REYNOLDS

INTRODUCTION

The manufacture, use, and disposal of organic-based explosives at military bases have resulted in soils contaminated with explosives residues. These include TNT, RDX, HMX, tetryl and other compounds. Composting is being studied as a means to decontaminate explosives-contaminated soils and may have the potential to be a cost-effective, environmentally safe, and readily implemented bioremediation technology. Requirements for using composting technology over a range of environmental conditions include increased knowledge of the extent of environmental influences on explosives-composting processes, an understanding of methods to control or mediate these influences, and the ability to successfully apply this knowledge on a practical scale. Sites having explosives-contaminated soils occur over a wide range of latitudes, and temperature has been shown to have a significant effect on microbially mediated processes involved in composting explosives-contaminated soils (Isbister et al. 1982; Doyle et al. 1986).

A research study was undertaken to evaluate and quantify the effects of subfreezing temperatures on the design and performance parameters of composting of explosives-contaminated soils. The study focused on four main areas: 1) a thorough review of available literature on composting, in general, with an emphasis on cold weather composting of explosives-contaminated soils, 2) an identification of parameters that influence design and performance of compost in cold climates, 3) an evaluation of the suitability of Louisiana Army Ammunition Plant (LAAP) compost design and structural integrity for use in cold climates, and 4) a determination of theoretical temperature distribution within a compost pile in a cold environment. Also, the literature review focused on the impact of cold climates on assessing the influence of engineering design on compost pile temperatures, and the control and measurement of these temperatures.

PURPOSE AND SCOPE OF STUDY

Objectives

The primary objective of this study is to provide pertinent information that would enhance engineering

design and performance of composting explosives-contaminated soils in cold-dominated areas. Secondary objectives include reviewing and documenting our current knowledge of general composting systems extensively used for municipal, industrial and solid wastes as well as those used for explosives-contaminated soils/sediments that would help achieve the aforementioned primary objective.

Scope of study

The study 1) reviews available literature for period 1941–1990 on composting, in general, with an emphasis on cold weather composting of explosives-contaminated soils, 2) identifies parameters that influence design and performance of compost in cold climates, 3) evaluates the suitability of Louisiana Army Ammunition Plant (LAAP) compost system design for use in cold climates, and 4) determines theoretical temperature distribution within a compost pile in a cold environment. It also provides recommendations on how to improve design and performance of composting system in cold climates.

Justification

There are several Army sites contaminated with explosives, including 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), N-methyl-N,2,4,6-tetranitroaniline (Tetryl) and the propellant nitrocellulose. Composting soil contaminated with TNT, RDX and nitrocellulose has been successfully demonstrated in the laboratory (Doyle et al. 1986) and in the field at LAAP (Roy F. Weston, Inc. 1986; Williams et al. 1988) to be viable and potentially cost-effective. In these studies, temperature was identified as a key factor controlling the rate of the biotransformation of explosives. In their field-scale demonstration of static pile composting to decontaminate explosives-contaminated sediments, Williams et al. (1988) said, "temperature was the primary test variable investigated." They also claimed that both the rate and extent of contaminant degradation in the compost piles tested indicated that the thermophilic temperature range (55°C) was superior to the mesophilic range (35°C). Hence, the effect of temperature needs to be always considered when planning for composting in cold environments, such as the compost pilot test at BAAP in northern Wisconsin.

During winter, all the northern U.S. states (including Wisconsin and Alaska) experience low (subfreezing) temperatures, which may have significant effect on the design and cost of composting systems at these locations. It has been projected that, by 1990, the cost of composting explosives-contaminated soil may be \$75–90 per ton (Bartell 1989). Low temperature, which usually causes freezing of soil for several months during winter, may increase this cost substantially. It may also affect the design and performance of the composting system, the composition of the compost mix, the compost pile mixing rate, the degree of aeration and moisture content. This study evaluates the impact of low temperature on these parameters and recommends methods to minimize the impact.

Potential benefits

One of the potential benefits of studying the effects of low temperature on composting is to improve the general knowledge of composting processes as well as to increase the data base on cold weather composting. The other potential benefit is in the operating cost of composting in cold climates. During winter, freezing of soil usually occurs for several months due to a long period of low temperature. Since low temperature may increase the cost of operation substantially, consideration of the low temperature impact on the design and performance of composting provides a *potential cost saving* for the cleanup of explosives-contaminated sites in a cold environment.

LITERATURE REVIEW

In order to effectively assess the effect of low temperature on composting explosives-contaminated soils, it is essential to establish an up-to-date knowledge of composting processes by reviewing the available literature on composting. An extensive review of available literature on composting, in general, with an emphasis on cold weather composting of explosives-contaminated soils has been reported by Ayorinde and Reynolds (1989a). A summary of the literature review is given in this report.

The review of available literature focuses on the influence of low temperatures on composting with emphasis on composting explosives, the influence of engineering design on compost pile temperatures, and the control and measurement of compost pile temperatures. In addition, the review includes a general discussion on composting, composting fundamental principles, available types of composting systems, applications of composting technology, and the established

parameters influencing composting under various environmental conditions that may be applicable to low temperature composting.

Definition of composting

A review of the literature indicates that there is no universal definition of composting. In a broad sense, Haug (1980) defines composting as the biological decomposition and stabilization of organic substrates under conditions that allow development of mesophilic temperature range (with an average of 35°C) and thermophilic temperature range (with an average of 55°C) as a result of biologically produced heat, with a final product sufficiently stable for storage and application to land without adverse environmental effects. Thus, composting has been traditionally regarded as a form of waste stabilization, but one that requires special conditions of moisture and aeration to produce thermophilic microbial growth.

According to Williams et al. (1988), composting explosives-contaminated soil is a biological treatment process in which soil and sediment are mixed with bulking agents and carbon sources to enhance microbial metabolism in degrading and stabilizing soil contaminants. Organic materials are biodegraded by microorganisms, resulting in the production of organic and/or inorganic by-products and energy in the form of heat. When applied to waste treatment or used for contaminant destruction and detoxification in soils, composting is a combination of biological and engineering processes.

The process of composting is readily classified into two broad categories. Aerobic composting is the decomposition of organic substrates in the presence of oxygen and is usually achieved by supplying air. The main products of aerobic metabolism are microbial biomass, carbon dioxide, water and heat. Conversely, anaerobic composting is biological decomposition in the absence of oxygen and yields the metabolic end products of methane, carbon dioxide and organic acids. In general, anaerobic composting releases significantly less energy per unit weight of organic material decomposed compared to aerobic composting, and anaerobic composting has a higher odor potential (Haug 1980).

Finsten et al. (1986b) differentiate between product-oriented composting, such as that used for producing a beneficial soil amendment, and treatment-oriented composting, such as that used as a component in an overall treatment plan. An example of the latter includes composting for volume reduction and material stabilization. Moreover, the authors clearly stress that the two composting uses have different goals. It is reasonable to question whether the two composting goals require different or similar process designs and controls.

Goals of composting

In municipal waste composting systems, the goal is to provide municipal waste decomposition in a manner that is cost effective, odor free, and environmentally sound (Epstein et al. 1976, Finstein et al. 1986b). Because aerobic composting surpasses anaerobic composting in meeting these goals, the preponderance of municipal waste composting research has centered on increasing the rate of the composting process. That is, faster aerobic composting rates are synonymous with achieving the desired goal of better cost efficiency.

In developing composting systems to treat toxic and hazardous wastes, a new goal, different from the two described by Finstein et al. (1986b), is distinguished. The goal of toxic and hazardous waste composting is to detoxify or render harmless the waste being composted (Ayorinde et al. 1990), in contrast to the treatment-oriented composting, the main goal of which is to achieve rapid volume reduction. In such composting systems, the hazardous waste compound may lack the organic substrates necessary to initiate spontaneous composting, and suitable organic substrates must be added. Although the goal in municipal waste composting is equivalent to maximizing the rate of organic substrate decomposition, the same may not be true for hazardous waste composting, in which the relationships among decontamination of different hazardous wastes and the decomposition rates of added organic substrates have not been clearly defined.

Biodegradation/biotransformation processes

The term "biodegradation" is often inappropriately used to describe the microbial transformation of compounds (Atlas and Bartha 1987). Frequently, the result of biotransformation of anthropogenic compounds is a synthesis of more complex products (Wood 1971, Brooks 1974, Sjöblad and Bollag 1981). Such products have been shown to result from composting explosives (McCormick et al. 1975, Kaplan and Kaplan 1982b). For clarity, this review will use the term "biodegradation" to mean complete or ultimate degradation of a substrate to carbon dioxide and inorganic mineral forms, such as ammonium. For other microbially mediated processes that do not culminate in such complete oxidation, the term "biotransformation" will be used. Notably, a series of biotransformations may be required to eventually yield biodegradation.

Biotransformation describes the transformation of a substrate to another compound or compounds. All biotransformation products may not be completely identified. They may be either more toxic than the original compound composted, nontoxic, or subject to further biotransformations or biodegradation under favorable

environmental conditions (Atlas and Bartha 1987). Moreover, different environmental conditions may favor formation of one or several products resulting in minimal formation of others (McCormick et al. 1975, Atlas and Bartha 1987). For poorly defined processes, biotransformation rates are much more readily measured than biodegradation rates. In general, monitoring biotransformation requires measuring only the disappearance or loss of the starting substrate. Confirming biodegradation requires monitoring $^{14}\text{CO}_2$ evolution from ^{14}C labeled contaminants or stringently controlled mass balancing. If ^{14}C labeled contaminants are not available, separation and analysis of a suite of possible by-products, some of which may be unknown or have no proven analytical methodologies, may be required. Much of the research on composting explosives in soils has determined only the disappearance of the starting substrate, and is therefore a measure of biotransformation rather than biodegradation.

Knowledge of the reactivity, toxicity, and stability of these transformation products is incomplete, although laboratory incubations involving ^{14}C labeled compounds have indicated that biodegradation accounts for only a slight portion of all biotransformation processes that occur during explosives composting (Isbister et al. 1982). There is also evidence that the biotransformation of explosives is a process of co-metabolism (Osman and Klausmeier 1972). This fact reinforces the view that the microbial activity in the pile is primarily associated with processes other than explosives metabolism. Furthermore, it suggests that, by better controlling these governing processes and understanding their relationship with reactions involving explosives and their metabolites, it may be possible to develop methods to advantageously influence the processes leading to complete and effective bioremediation of explosives.

Composting design and technology

Almost all the existing compost design concepts were developed for composting municipal and industrial solid wastes. These types of solid wastes usually consist of wet feed substrates that are difficult to compost alone because of the high moisture content. Hence, the general schematic diagram for composting is represented as shown in Figure 1. The fundamental concepts embodied in Figure 1 underlie all composting systems and their operations; therefore, they are applicable to the composting of explosives-contaminated soils or sludge.

Classification of composting systems

Composting systems can be classified according to the reactor type and nonreactor type, solids flow mecha-

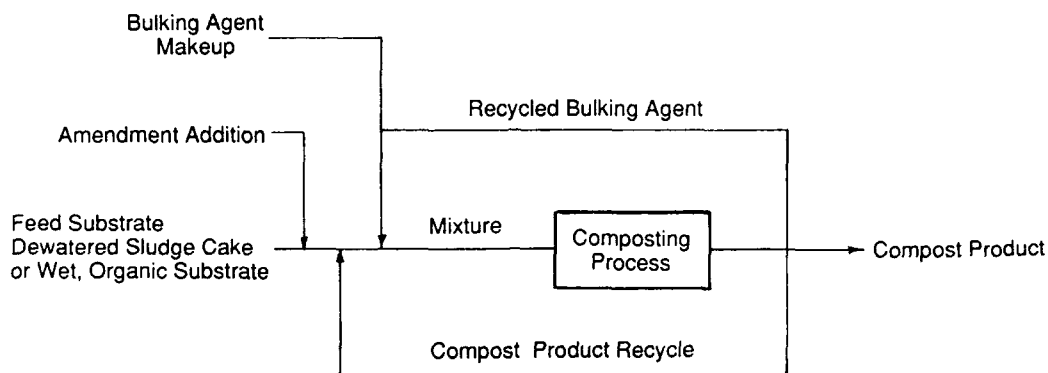


Figure 1. Generalized diagram for composting, showing inputs of feed substrate, compost product recycle, amendment and bulking agent (Haug 1980).

nisms, bed conditions in the reactor and manner of air supply. All of the available systems have advantages and disadvantages relative to one another. The nonreactor ("open") systems consist of those that maintain an agitated solids bed and those that employ a static bed as

shown in Figure 2. In the compost systems with an agitated solids bed, the compost mixture is disturbed or broken up in some manner during the compost cycle.

Reactor systems, on the other hand, are usually termed "mechanical," "enclosed" or "within-vessel"

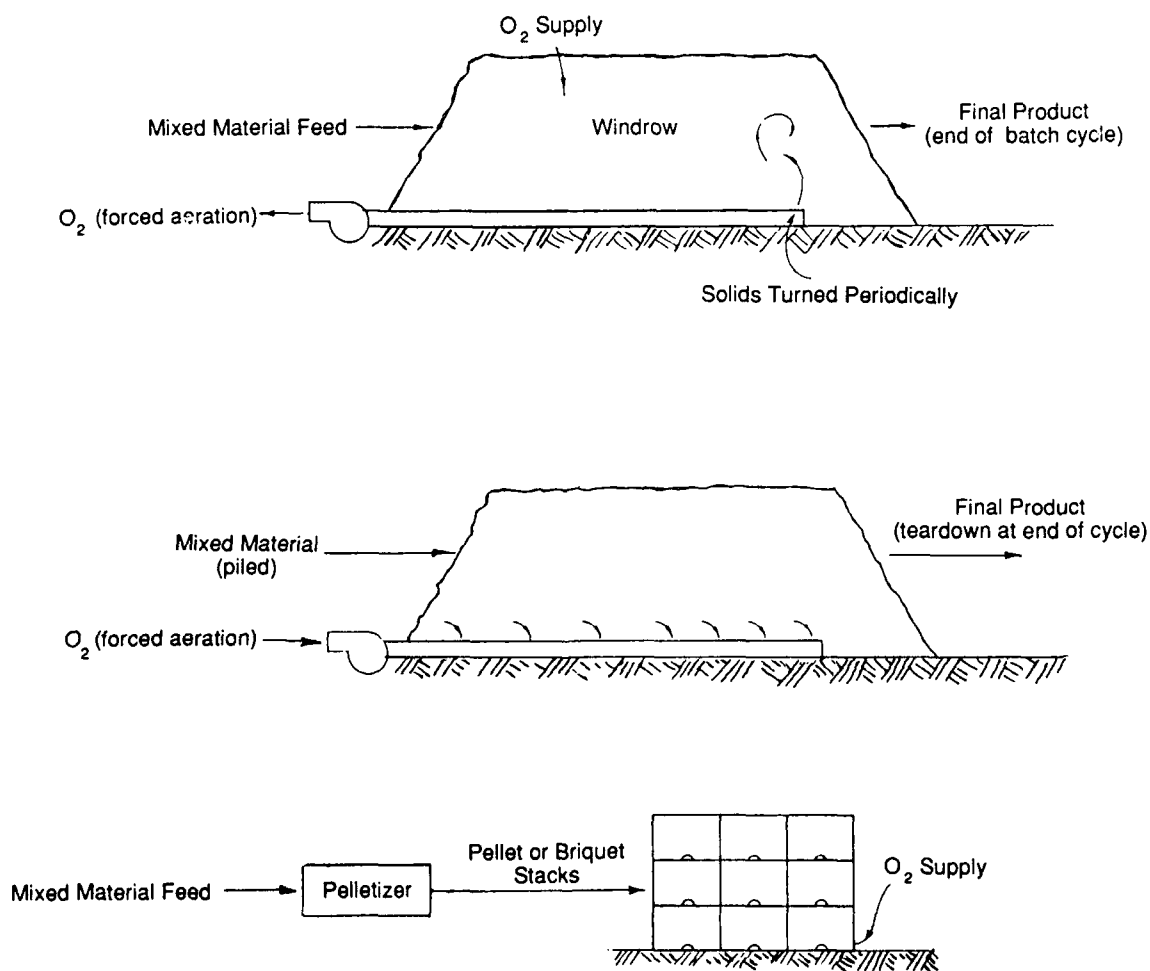


Figure 2. Nonreactor composting systems (Haug 1980).

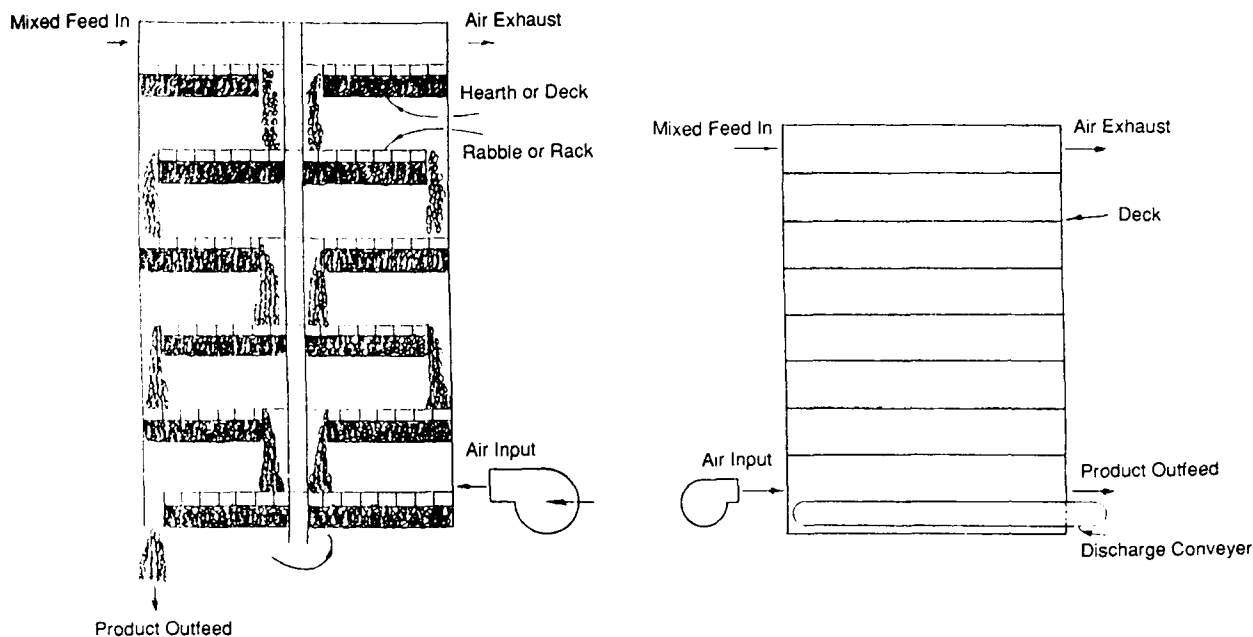


Figure 3. Vertical flow reactor systems, moving agitated bed tower or silo reactors (Haug 1980).

composting systems (Haug 1980). The term “mechanical” is a misnomer because most modern composting systems, including nonreactor systems, are mechanical to some extent. Figures 3–6 illustrate the different types of reactor systems. A classification scheme, which can be used to classify any type of composting system, has

been developed (Haug 1980). The classification scheme includes 1) nonreactor (open) systems consisting of agitated solids bed (windrow) and static solids beds, 2) vertical flow reactor systems (tower reactors) consisting of moving agitated beds and moving packed beds, and 3) horizontal and inclined flow reactor systems

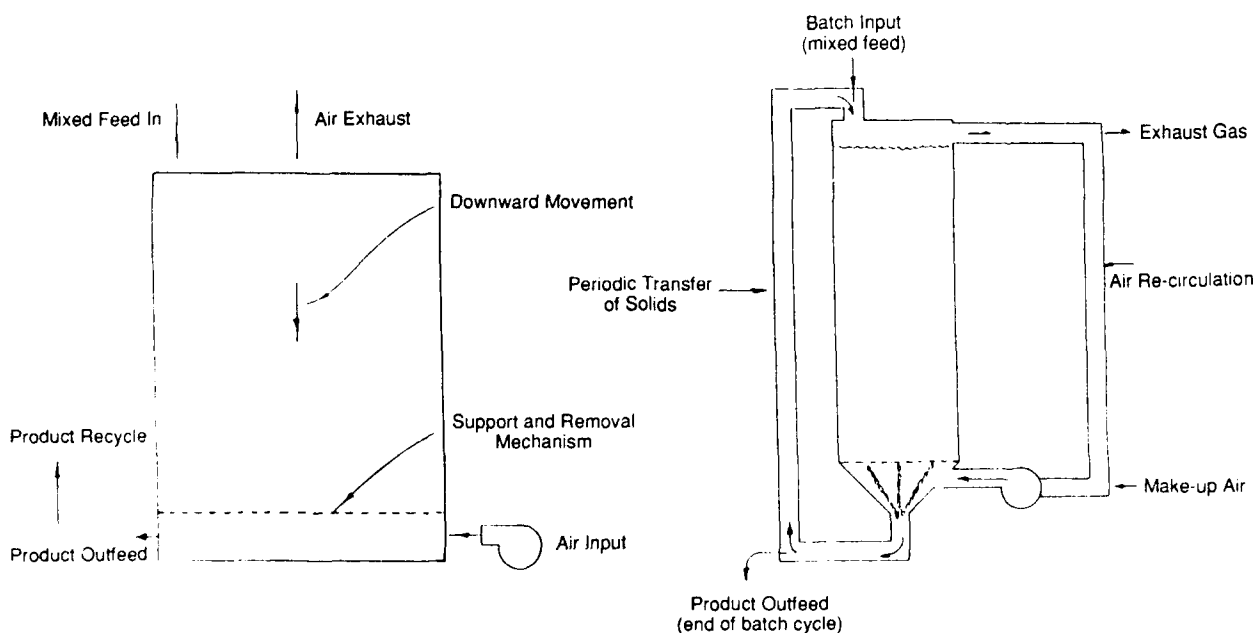


Figure 4. Vertical flow reactor systems, moving packed bed tower or silo reactors (Haug 1980).

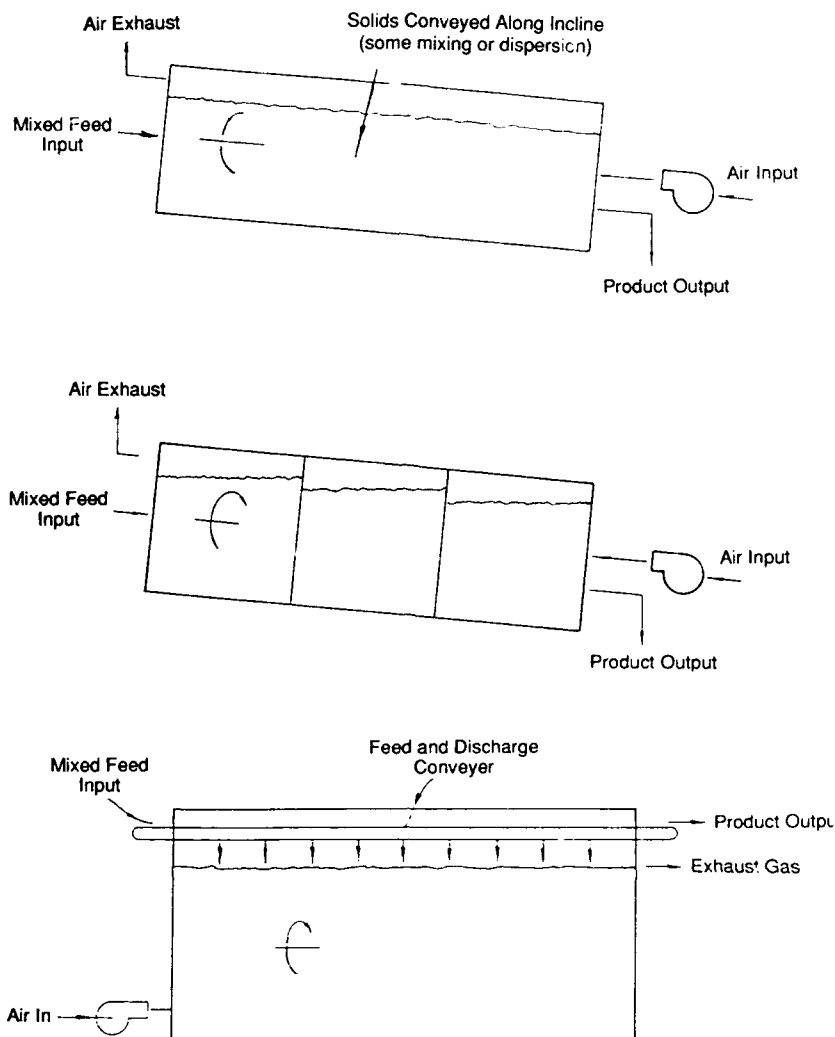


Figure 5. Horizontal and inclined flow reactors, tumbling solids bed reactors (Haug 1980).

consisting of tumbling solids beds (rotating drums) and agitated solids beds (bin reactors). A general comparison between various composting processes is given in Table 1. It should be noted that composting of hazardous waste has only been recent and limited, and that, to date a hazardous waste reactor composting system has not been used.

Design of composting systems

The design of composting systems can be classified into six categories: 1) windrow composting, 2) static pile composting, 3) enclosed composting 4) in-vessel composting, 5) bin composting, and 6) mechanical or high rate composting (Finsten et al. 1986b, 1987c). According to the above classification scheme, windrow

composting, aerated static pile composting and enclosed composting are classified as "nonreactor" systems, while the in-vessel composting, the bin composting and the mechanical or high rate composting are classified as "reactor" systems.

In windrow composting, an elongated unenclosed pile is subjected to mechanical agitation by means of a turning machine (windrowing) or front-end loader. No mechanical agitation is used for static pile composting, and pile dimensions in static pile composting are usually larger than in windrow composting. For enclosed composting, material is sheltered, but not held in a special vessel; the processing technique is similar to the windrow or static pile methods. Bin composting is a form of in-vessel composting where material is held in

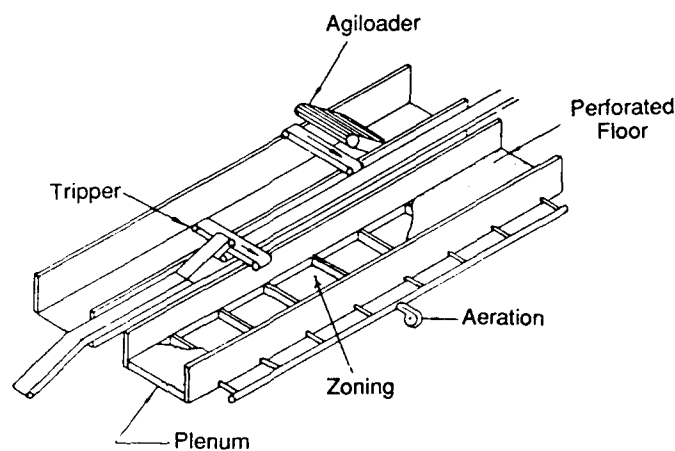
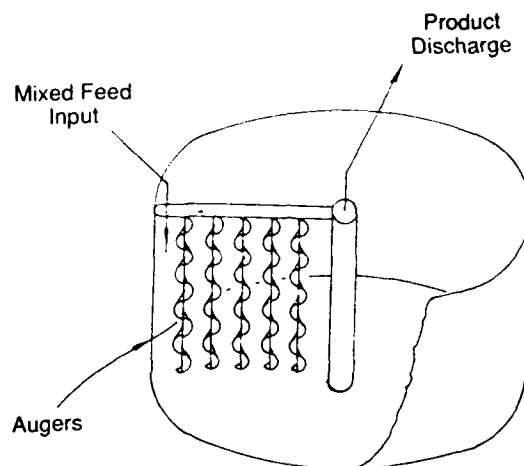


Figure 6. Horizontal and inclined flow reactors, agitated bed reactors (Haug 1980).

a special vessel for better control of agitation, ventilation, residence time, batch or processing mode, material handling and curing.

Because there is a potential for explosion in any system containing explosives, caution should be exercised if any one of the above-noted mechanical systems is used for composting explosives-contaminated soils and wastes. It is therefore recommended that a careful and adequate design analysis be performed when adopting any type of mechanical system for composting explosives-laden soils or wastes.

To better control the composting environment, in-vessel or reactor-type compost systems appear reasonable. At the time this report was prepared, in-vessel composting for explosives was considered infeasible

due to its explosion potential. Consequently, in-vessel or reactor composting was not considered in detail in this report. However, a detailed description of a bin composting system design and operation for municipal solid wastes is given below since, at that time, it was one of the systems being considered for a potential field design operation for composting explosives-contaminated soils.

Bin composting design and operation

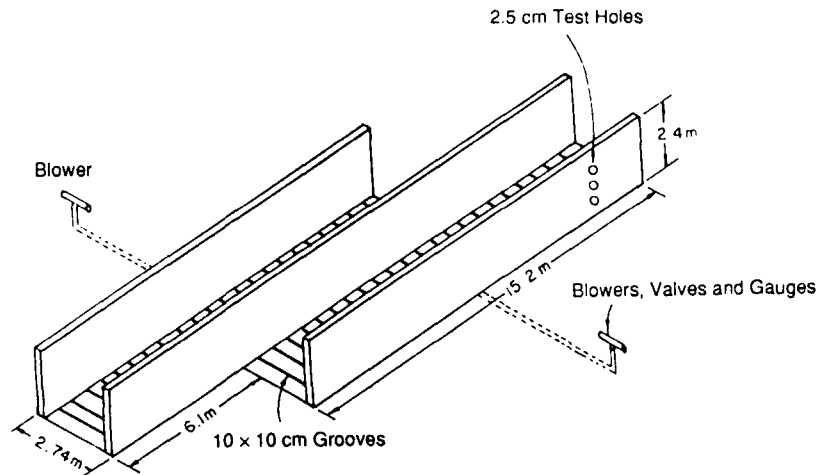
Senn (1971) reported the use of bin-type composting (horizontal flow, agitated solids bed reactor) with wet organic feed materials to compost dry dairy manure. The system was designed to provide agitation of the material during the compost cycle and a forced aeration

Table 1. Comparison between various composting processes when used for sludge composting (Haug 1980).

| Item | Nonreactor systems | | Reactor systems | |
|---------------------------------------|--|---|--|---|
| | Windrow | Aerated pile | Forced aeration, plus agitation | Forced aeration, no agitation |
| Capital costs | Generally low | Generally low in small systems; can become high in large systems | Generally high | Generally high |
| Operating costs | Generally low | High, depending largely on bulking agent used | Generally low | Generally low |
| Land requirements | High | High | Low, but can increase if windrow drying is required | Low, but can increase if windrow drying is required |
| Control of air supply | Limited unless forced aeration is used | Complete | Complete | Complete |
| Operational controls | Turning frequency, amendment or compost recycle addition, forced aeration rate | Air flowrate, bulking agent addition | Air flowrate, level of agitation, amendment or compost recycle addition | Air flowrate, amendment or compost recycle addition |
| Sensitivity to de-watered cake solids | More sensitive | Less sensitive | Less sensitive | Less sensitive |
| Need for subsequent drying | Drying usually occurs in windrow but depends on climate | Drying can be achieved in pile with high air supply; windrow drying may be required | Drying can be achieved in reactor; final drying in windrow or heat dryer may be required | Less drying potential from lower air flow rates; final drying in windrow or heat dryer usually required |

| Sensitivity to cold or wet weather | Sensitive unless in housing; demonstrated mainly in warm, dry climates | Demonstrated in cold and wet climates | Demonstrated in cold and wet climates |
|-------------------------------------|--|--|--|
| Demonstrated on digested sludge | Yes | Yes | Yes |
| Demonstrated on raw sludge | Yes, but odor problems observed | Yes | Yes |
| Need for amendment or bulking agent | Well demonstrated using recycled compost only | All designs to date use bulking agents; pilot operations used recycled compost with digested sludge | Amendment addition along with recycled compost usually used |
| Control of odors | Depends largely on feedstock; potential large-area source | Handling of raw sludge is potentially odorous; may be large-area source | Potentially good |
| Potential operating problems | Low cake solids will increase odor potential and cause reduced temperature in windrows; susceptible to adverse weather | Mixing and screening of bulking agent can be difficult; anaerobic balls sometimes observed; wood chips can harbor opportunistic fungal pathogens | Potential problems of sludge compaction and channeling or short-circuiting of air supply; system may be mechanically complex |

Figure 7. Aerated bins used in field composting tests on dairy manure. Bins were staggered and sized for transferring and unloading by conveyor buckets and belt of Eagle Loader (Senn 1971).



in the floor of the bins as indicated in Figure 7. Normal aeration rates were 6.7 m^3 of air/hr m^3 of the manure. Maximum static pressures were about 15 cm of water gauge (which is equivalent to 150 kgf/m^2). A composting time of 2–7 days was provided in each bin followed by a minimum 30-day period in stockpiles.

Senn gave a typical temperature profile (Fig. 8) developed under optimum moisture and air flow conditions. He noted that rapid temperature elevations within the first 24 hr were characteristically observed.

According to Senn (1971), the most rapid production of attractive, stable compost was found to occur at

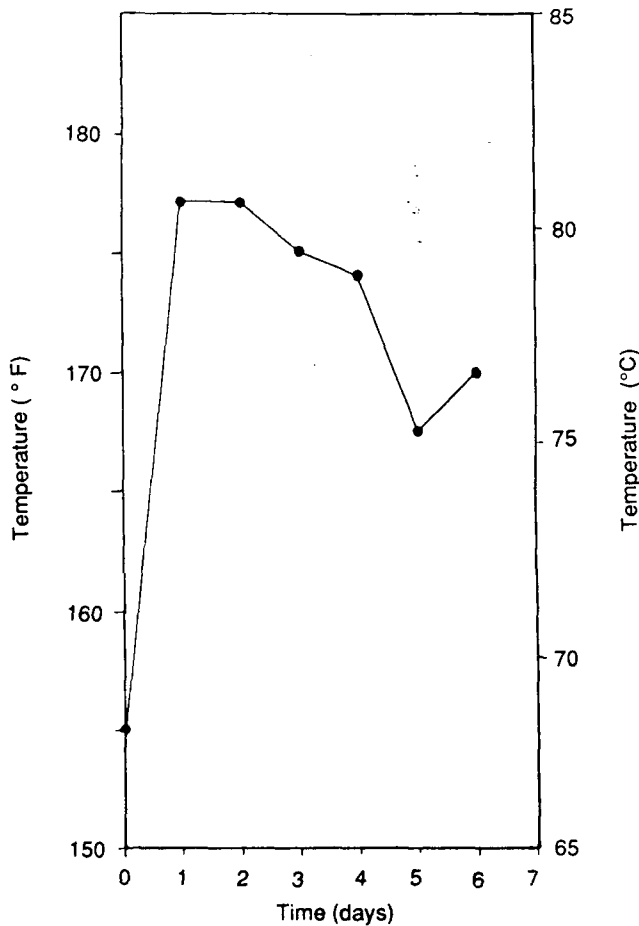


Figure 8. Typical temperature developed during bin composting of dairy manure under conditions of constant airflow and optimum moisture (Senn 1971).

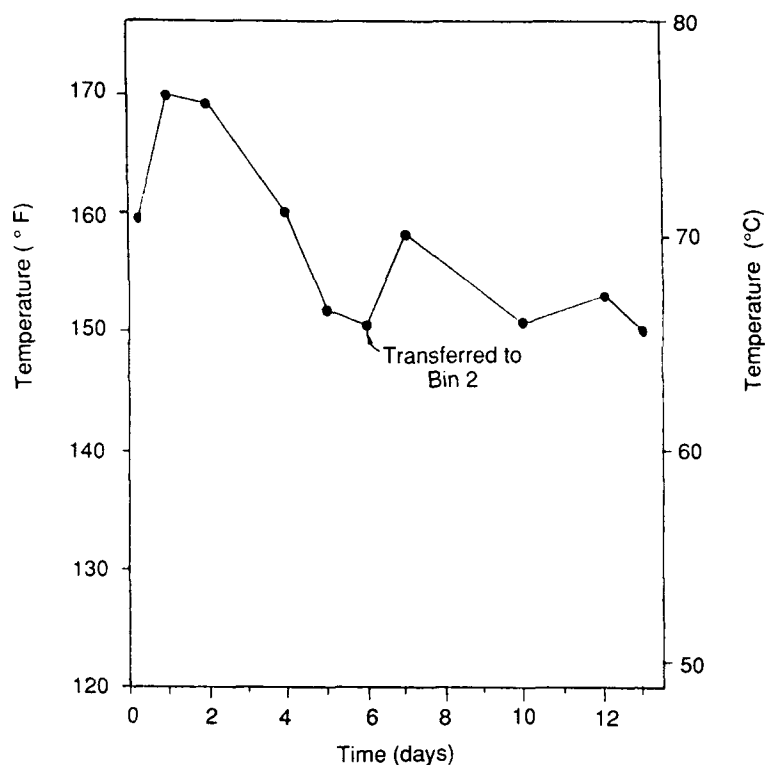


Figure 9. Effect of agitation on the temperature profile during bin composting of dairy manure. Moisture content was 50% and air flow rate was held constant. During composting, 1) rapid temperature rise to 70°C occurred in 6 hr, 2) flow rate temperature drop was graded and could be stopped by lowering air flow rate, and 3) the temperature rise was caused by mixing and loosening from transfer (Senn 1971).

temperatures between 71° and 79°C. Even though temperatures as high as 87°C were measured, composting above 79°C produced an end-product considered undesirable due to the resulting dark color and unpleasant, "cooked" odor. Optimum gravimetric moisture content was found to be in the range of 50–56% moisture. However, the material was successfully composted if loaded at moisture contents of 45–60%. A phenomenon commonly observed during the operation that might impact the explosives-contaminated soils composting was the "packing" of material in the bins, particularly at high moisture contents. The transfer of material from one bin to another loosened the material, allowing increased temperature development as indicated in Figure 9. Agitation was also found to be effective in loosening the material so that higher air flow rates could be maintained, which, in turn, resulted in a higher rate of heat removal, thus lowering the high temperature buildup to a more optimum range. As expected, it was found that low air flow rates could lead to excessively high temperatures, which limited the compost biological activity.

Iacoboni et al. (1977) and LeBrun et al. (1978) provided data from the compost experiment sponsored by Los Angeles Orange County Metropolitan Authority in which dewatered municipal sludge was composted in a bin-type system with bed depths of 2.5–3 m (Fig. 10 and 11). As with manure composting, it was observed

that the initial solid content of the mixture used was important in order to achieve rapid temperature rise. The effect of the initial mixture solid content on the temperature profile is shown in Figure 11. The data showed that an initial mixture with 50% solids was considered near optimum compared with 45% solids content (LeBrun et al. 1978).

Haug (1980) discussed another bin-type composting system operated at the Minamitama Sewage Treatment Plant (MSTP), Japan, where the feed material consisting of raw sludge was conditioned with lime and ferric chloride, and then dewatered by filter press to about 35% cake solids. What is unique about the MSTP operation was that the dewatered sludge was blended with recycled compost product to achieve an optimum 50% solids mixture, which was then composted for ten days. Compost product was used for feed conditioning primarily because other additives such as "wood chips" were not consistently available. This may be relevant to a large field operation for composting explosives-contaminated soils.

Performance evaluation of composting systems

Most researchers concur that the evaluation of municipal waste composting process performance is centered on the issue of decomposition rate, with higher rates generally desirable. In other words, decomposition rate is an overriding determinant of composting

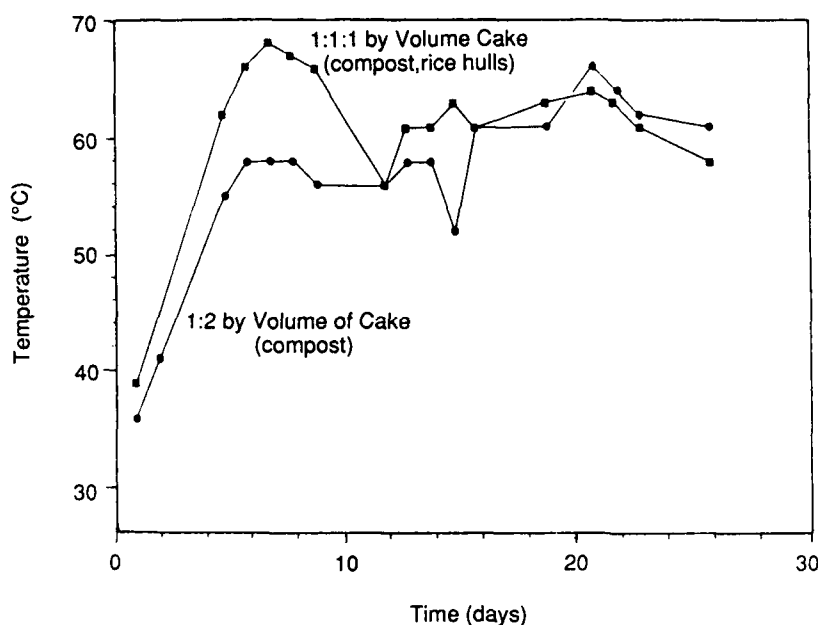


Figure 10. Average temperatures observed during bin composting of digested sludge cake mixtures. Sludge cake was approximately 25% solids and recycled compost about 65% solids. Each data point represents an average of 17 temperature readings over the cross section of the reactor (Iacoboni et al. 1977).

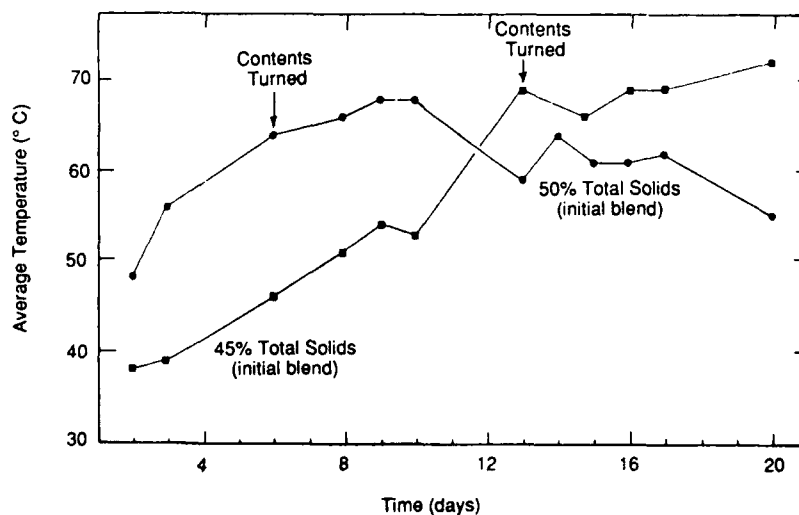
process performance. Evaluation of compost product quality is also essential (Finsten et al. 1986a,b). The absence of a decomposition rate measure in composting tends to contribute to suboptimal process design and control, erratic operational performance, and odor problems.

A review of composting process-performance evaluation by Finstein et al. (1986a) indicated that tests involving organic content (volatile solids, organic carbon, chemical oxygen demand [COD], biochemical oxygen demand [BOD], starch, and cellulose) lack sensitivity, specificity and general relevance. Tests that tend to quantify some decomposition (heat output,

metabolic-water production, oxygen consumption, and carbon dioxide production) are generally inapplicable in routine field practice for industrial and municipal solid wastes. As for the composting of explosives-contaminated soils and sludges, the potential problems tend to become more difficult because of the complex nature of the biodegradation and biotransformation processes of the organic compounds that need to be decomposed.

Although the biotransformation of explosives occurs most rapidly under thermophilic conditions, there is a paucity of information on the fate of the biotransformation products and how environmental factors within

Figure 11. Effect of initial mixture solids content on the temperature profile during bin composting of digested sludge cake blended with recycled compost. Each data point represents an average of 17 temperature reading over the cross section of the reactor (LeBrun et al. 1978).



the composting may influence the direction and rate of these processes. Because temperature has a profound effect on microbial diversity, kinetics, and metabolites, a system that provides for a more uniform and responsive temperature distribution might be employed to direct the composting process in a way most favorable to desired goals. From published research to date, it is clear that composting at thermophilic temperatures approaching, but not exceeding, approximately 55°C results in the most rapid biotransformation of explosives. What is not at all clear is how best to manipulate temperatures, as well as other parameters, to best render harmless the products from the biotransformation of explosives.

Recent work by Berardesco and Finstein (1988) has clearly demonstrated that polyaromatic hydrocarbon transformation ability was present in a greater percentage of the microbial population at mesophilic temperatures than at thermophilic temperatures. In contrast to the generally accepted rationale that "faster composting is better," the development of a hazardous waste composting system that enables more uniform and precise control of composting temperatures to be maintained for extended time periods may prove to have applications beyond those that are currently obvious.

PARAMETERS AFFECTING COMPOSTING

General composting

A number of studies in the literature (Bhoyar et al. 1979; Haug 1980 1986a,b,c; Cathcart et al. 1986; Finstein et al. 1986a,b 1987a,b,c) have addressed the importance of environmental conditions and parameters affecting composting. Most of these studies were based on agricultural, municipal and industrial solid wastes at temperatures above freezing. The parameters that consistently have been found to significantly impact the efficiency of the composting process include the following: temperature, moisture content, aeration, organic and inorganic nutrients, chemical and biological characteristics, availability of substrates, substrate concentration and ratio of concentrations, heat production and retention characteristics of the compost, and the partial pressure of oxygen within the compost material. However, to date, no research information or data are found in the literature on the sustained effect of a cold climate on composting. The four major parameters identified are discussed in detail below.

Temperature

Among the interrelated factors influencing composting processes, temperature is perhaps the most significant. The temperature within a composting sys-

tem is a function of the accumulation of heat generated metabolically, and simultaneously the temperature is a determinant of metabolic activity. Hence temperature is both a cause and an effect in terms of the heat output in a self-heating ecosystem of compost and governs the self-limiting conditions for microbial activity (MacGregor et al. 1981). The interaction between heat output and temperature is therefore the centerpiece of rational control of the composting system (Haug 1980, Bhoyar et al. 1982; Finstein et al. 1986a,b, Williams et al. 1988). Almost all the referenced studies on the temperature effect were conducted in high mesophilic to thermophilic (35–55°C) temperature ranges.

Studies have generally concluded that thermophilic conditions ranging from approximately 40–60°C are desirable for composting (Sikora and Sowers 1985, Finstein et al. 1986a,b). These conclusions are generally based on studies of municipal wastes in which decomposition was determined by CO₂ evolution or substrate mass reduction. In such a system, thermophilic conditions are desirable for both rapid decomposition and pathogen destruction. Although thermophilic conditions up to approximately 60°C generally result in faster microbial metabolic rates than those under mesophilic conditions (Finstein et al. 1986a,b), there is evidence that microbial diversity may be reduced as conditions become increasingly thermophilic (Strom 1985). Owing to the natural predominance of mesophilic conditions and microbial specificity for substrates, reduction in microbial diversity may result in less complete oxidation and reduced net biodegradation of complex substrates.

Among several composting studies that have focused on explosives, few have been conducted at temperatures lower than thermophilic. This is understandable considering the natural tendency of a compost pile to reach a thermophilic regime, the desirable faster metabolic rates that result, and the realization that the considerable volume of published research has been primarily aimed at composting municipal waste. Kaplan and Kaplan (1982a) compared the mesophilic-biotransformation products of TNT (McCormick et al. 1975) to those resulting from thermophilic incubation conditions (Kaplan and Kaplan 1982b) and found them to be similar. Using the Synthetic Precipitation Leach Test method, Griest et al. (1989) tested leachates from composted explosives-contaminated wastes and found greater toxicity in mesophilic compost leachate than in thermophilic leachate. Because the composting lasted only 22 weeks with no controls included in the compost operation (Williams et al. 1988), it cannot be determined if the greater toxicity of the mesophilic compost leachate was due to either explosives or greater fungal production of antibiotics in the mesophilic compost, or

whether sufficient time had been allowed for mesophilic composting to stabilize.

Empirical methods for estimating heats of reaction during composting. In the composting of municipal, industrial or hazardous/toxic wastes, mixtures used usually comprise several organic compounds of unknown composition. Hence, it is often difficult to estimate the heats of reaction from organic wastes from standard enthalpy values, since the mixture composition is not completely known. Even if it is known, the enthalpy values would only help to define a range of probable heats of reaction. As a result, several experimental and empirical techniques have been developed to determine heat of reaction.

One experimental method for determining the heating value of organic waste is by calorimetric measurement, which is undoubtedly the most accurate way of determining heats of reaction for organic mixtures (Haug 1980). This technique consists of either 1) an "open calorimeter" in which the heat of chemical reaction is measured at a constant pressure of one atmosphere, or 2) a "bomb calorimeter" in which reactions are conducted under constant-volume conditions. Even though the heat release in a bomb calorimeter would be different from that in a constant-pressure calorimeter, the differences are usually small for organic materials that release considerable energy on oxidation (Lee and Sears 1963).

An experimentally based empirical formula for determining the fuel values of different types of vacuum-filtered sludges was formulated by Fair et al. (1968):

$$Q = a[(100 \times P_v)/(100 - P_c) - b] \times [(100 - P_c)/100] \quad (1)$$

where Q = fuel value, Btu/lb dry solids

a = 131 and b = 10 for both raw and digested primary sludge

a = 107 and b = 5 for raw waste activated sludge

P_v = percent volatile solids in sludge

P_c = percent of inorganic conditioning chemical in sludge.

Data used to derive eq 1 were obtained from a constant-volume bomb calorimeter. Although eq 1 was developed only for municipal sludge and should not be extended to other organic wastes, this approach may be applicable to hazardous waste composting.

Spoehr and Milner (1949) presented a formula that relates the heat of combustion to the degree of reduction of organic matter. Products of combustion are assumed to be gaseous carbon dioxide (CO_2), liquid water (H_2O), and nitrogen (N_2). Thus, the degree of reduction (DR)

for any organic matter is given by:

$$DR = [100 \times (2.66C + 7.94 H - O)]/398.9 \quad (2)$$

where C, H, O are the percentages of carbon, hydrogen and oxygen, respectively, on an ash-free basis. The heat of combustion (Q) is given by:

$$Q \text{ (cal/g)} = 127 \times DR + 400. \quad (3)$$

Corey (1969) presented the Dulong formula which is sometimes useful for estimating gross heating values for the feed composition:

$$Q \text{ (Btu/lb)} = 145.4(C) + 620 \times (H - O/8) + 41(S) \quad (4)$$

where S is the percentage of sulfur.

It should be noted that eq 3 and 4 require a fairly complete laboratory analysis of the waste to accurately determine the percentages of carbon, hydrogen, oxygen and sulfur. These data may not be available routinely. A list of heat contents of dry refuse and sewage sludge samples is given in Table 2.

Reaction rates and effect of temperature. Biological, biochemical and chemical reaction rates in composting system are usually a function of temperature. Above mesophilic and within thermophilic temperature ranges, it has been shown that there is faster microbial activity leading to a rapid generation of heat (Finstein et al. 1986b). Haug (1980) noted that a convenient way of

Table 2. Representative chemical analysis and heat content of dry refuse and sewage sludge samples (Haug 1980).

| Constituent | Refuse (wt %) | Raw sludge (wt %) | Digested sludge (wt %) |
|----------------------------------|------------------|-------------------------|------------------------------|
| Carbon | 33.11 | 37.51 | 24.04 |
| Hydrogen | 4.47 | 5.54 | 3.98 |
| Oxygen | 25.36 | 22.56 | 12.03 |
| Nitrogen | 0.60 | 1.97 | 2.65 |
| Chlorine | 0.41 | 0.33 | 0.17 |
| Sulfur | 0.14 | 0.37 | 0.75 |
| Metal | 11.64 | — | — |
| Glass, ceramics, stone | 16.23 | — | — |
| Volatiles @110°C | — | 3.66 | 3.01 |
| Ash | <u>8.04</u> | <u>28.06</u> | <u>53.37</u> |
| | 100.00 | 100.00 | 100.00 |
| Higher heating values (cal/g) | 3280 | 3190 | 2570 |

expressing the temperature effect is to determine and compare the rate of activity at one temperature to the rate at a temperature 10°C lower. The resulting ratio is known as the temperature coefficient, Q_{10} . Within certain limits which can be easily established if the Arrhenius equation is used, the rates of most chemical reactions approximately double for each 10°C rise in temperature (with Q_{10} approximately equal to 2.0).

The effect of temperature on chemical reactions on the rate constants for chemical reactions can be estimated using the Arrhenius equation:

$$d(\ln k)/dT = E_a/(RT^2) \quad (5)$$

where k = reaction rate constant

E_a = activation energy for the reaction, cal/mol

T = absolute temperature, K

R = gas constant, cal/(mol)(K).

Activation energy is defined as the amount of energy needed by a molecule to undergo a successful chemical reaction.

Integrating eq 5 yields

$$\ln(k_2/k_1) = E_a(T_2 - T_1)/RT_1T_2. \quad (6)$$

In composting systems, most biological and biochemical processes operate within a limited range of temperatures. Since the product of T_1 and T_2 changes only slightly over the biological temperature range (e.g., 0 to 80°C, which is equivalent to 273 K to 353 K), E_a/RT_1T_2 can be assumed constant. Hence, eq 6 can be written as

$$\ln(k_2/k_1) = \theta(T_2 - T_1) \quad (7)$$

i.e.

$$k_2 = k_1 \exp[\theta(T_2 - T_1)] \quad (8)$$

where θ is assumed to be reasonably constant. However, Haug (1980) indicated that θ has been found to vary considerably even over small temperature ranges. He suggested that applicable temperatures should be clearly stated for values of θ used in eq 7 and 8. For comparison, a θ of about 0.069 corresponds to a Q_{10} of 2.0.

Moisture content

In composting systems, decomposition of organic matter depends upon the presence of moisture to support microbial activity. It has been suggested that the theoretical ideal moisture content for composting would be one that approaches 100%, because under such

conditions, biological decomposition would occur in the absence of any moisture limitation (Golueke 1977). Hence, maintaining a proper moisture balance is a critical factor in the design of sludge or any other organic substrate composting system. The thermodynamic balance of the composting system and the ability to aerate the compost material are greatly influenced by proper moisture content (Atchley and Clark 1979, Haug 1980, Jacobowitz and Steenhuis 1984).

Optimum gravimetric moisture content levels for composting have been reported to range from 50 to 70% (McKinley and Vestal 1985). Bakshi et al. (1987) found that 70% gravimetric moisture content provided the most suitable conditions for natural fermentation of urea-treated straw. For composting explosives-contaminated soils, Williams et al. (1988) used a range of 20 to 56% gravimetric moisture content.

Due to the heterogeneity of compost mixtures, the use of percentage water content rather than water potential is, at best, merely a gross approximation of the water characteristics of the compost system; hence it prevents comparing moisture effects from published results or transferring experimental results to other situations. Miller (1989) has shown that the matrix water potential method quantified compost moisture requirement better than the gravimetric moisture content method. The water available for microbial processes is dependent on not only the amount of water in the system but also the solution or water osmotic potential, the sorptive capacity, and hygroscopicity of the matrix. Consequently, at a given gravimetric moisture content, the available water can vary significantly, depending on solute concentration and the texture and quantity of soil added to a compost mixture, as well as the texture and nature of the compost bulking agents used. Despite the lack of quantitative data, it is well established that ventilation used for heat removal causes drying, and water must be added to the compost system (Finstein et al. 1987a,b,c). Available literature does not provide sufficient data to interpolate the optimum water potential for explosives biotransformation in composting systems that consist of blends of soil and bulking agents.

Aeration

Composting is an exothermic process that increases the temperature in the system; temperature, in turn, is a determinant for microbial activity rates, thereby influencing heat output. These coupled, feedback processes effectively raise compost-pile temperatures sufficiently high to inhibit the active microbial population and temporarily inhibit the composting process. To counter the heat production effect on temperatures, forced ventilation is generally employed (Macgregor et al. 1981). Ventilation promotes cooling both by convec-

tion and, to a much greater extent, by evaporation. Ventilation also serves to promote aerobic conditions, thus favoring faster aerobic metabolic pathways and rates that are associated with aerobic processes. Although there is significant evidence that RDX biotransformation is an anaerobic process (McCormick et al. 1981), there is a general agreement that aerobic conditions should be favored in the composting pile (Finstein et al. 1987a,b,c, Williams et al. 1988). Ventilation and the subsequently induced evaporation dry the system to a degree that is inhibitory to microbial activity unless water is added to the system.

Heat removal mechanisms during composting. To develop and design an effective system for a large field-scale composting of explosives-contaminated soils, a heat removal and control technique has to be used to moderate a large temperature buildup caused by heat generation during composting. According to Finstein et al. (1986b), the heat removal mechanisms that occur during composting include radiation, conduction, vaporization of water (evaporative cooling), and sensible heating (temperature increase of dry air). Hence

$$Q_{\text{tot}} = Q_{\text{rad}} + Q_{\text{cond}} + Q_{\text{vent}} \quad (9)$$

where Q_{tot} is the total heat removal, Q_{rad} is the radiant removal, Q_{cond} is the conductive removal and Q_{vent} is the ventilative removal. The sum of conductive and radiative heat removal is very small compared to the ventilative heat removal, and therefore can be neglected in eq 9. Hence, the total heat removal can be equated to the ventilative heat removal. The relationship governing ventilative removal is given by

$$Q_{\text{vent}} = m(H_{\text{out}} - H_{\text{in}}) \quad (10)$$

where Q_{vent} = rate of ventilative heat removal, (energy/time)

m = dry air mass flow rate, (mass dry air/time)

H_{out} = outlet air enthalpy, (energy/mass dry air)

H_{in} = inlet air enthalpy, (energy/mass dry air)

The enthalpy of the air is a function of both its temperature and relative humidity (RH).

Effect of ventilation on composting. Ventilation, whether forced or natural, supplies oxygen required to support aerobic biological activity in composting. The stoichiometric oxygen demand will depend on chemi-

cal composition of the organic material. For municipal sludge, a value of approximately two grams of oxygen per gram (i.e., 2 g O₂/g) of organic material oxidized is assumed reasonable (Haug 1980, Kuter et al. 1985). Also, it has been found that, compared to natural ventilation in windrow composting systems, forced ventilation by means of blowers is the major aerating mechanism in the aerated static pile and many reactor systems.

Furthermore, the use of a blower to force air through a composting pile increases ventilative heat removal, leaving conduction to play a minor role in removing the generated heat. In addition, vacuum-induced ventilation is commonly used for odor control by venting the outlet air through a "scrubber pile" consisting of aged or stabilized old compost (Epstein et al. 1976). Two mechanisms that account for heat removal rate through ventilation, Q_{vent} , (energy/time) consist of 1) heat removal rate through vaporization, Q_{vap} , (energy/time) and 2) heat removal rate through sensible heating of air, Q_{sens} , (energy/time). Thus

$$Q_{\text{vent}} = Q_{\text{vap}} + Q_{\text{sens}} \quad (11)$$

Assuming outlet air at 60°C temperature and a relative humidity (RH) of 100%, Finstein et al. (1986b) estimated that

$$Q_{\text{vap}} = 9 \times Q_{\text{sens}} \quad (12)$$

From eq 10, 11 and 12, the vaporization heat removal rate can be estimated as

$$Q_{\text{vap}} = 0.9 \times m(H_{\text{out}} - H_{\text{in}}) \quad (13)$$

No information was available on research that investigated the impact on compost biological activity of forced or natural ventilation of air far below the mesophilic temperature or close to the freezing temperature.

Organic content and inorganic nutrients

Microbial activity of a composting system is directly influenced by the organic content and inorganic nutrients of the composting material (Haug 1980, 1986a,b,c; Finstein et al. 1987a,b,c.). Cathcart et al. (1986) conducted experiments to determine the optimum value of the carbon-nitrogen ratio of material used as a nutrient for the composting of solid waste (crab scrap).

The effects of different types of inoculum and mineral concentrations were found to profoundly affect the composting activity of synthetic solid waste in the thermophilic temperature range (Clark et al. 1978).

Cold weather composting

There is a scarcity of information on the effect of low temperatures on compost operation and performance. No published data are available to help establish the low temperature level at which composting microbial activity would cease. It is generally acknowledged by researchers that a low starting temperature (cold start) tends to prolong the start-up stage. Finstein (1986b) reported that, at an ambient temperature of 9° to 17°C, it took two to six days for a composted sludge/woodchip mixture to reach 55°C, while at -17° to 0°C, it took seven to 18 days. It appears that minimal starting ventilation was used to speed the temperature ascent to more biologically favorable levels. The authors claimed that a compost material initially at 0°C reached thermophilic temperature in 4½ days. However, no quantitative evidence was offered by the authors to support this claim.

Nevertheless, it appears that marginally effective composting can spontaneously occur at low temperatures if necessary oxygen and water are present, and the compost mass is sufficient to retain heat. However, to date, no research information or data are found in the literature on the sustained effect of a cold climate on composting.

As noted earlier, the majority of published research has been concentrated on the composting of municipal and industrial solid wastes, with relatively few studies on composting hazardous-toxic wastes. In fact, Williams et al. (1988) have reported the only field-scale data on the composting of explosives-contaminated soils at temperatures above freezing. Recently, Ayorinde and Reynolds (1989b) presented results of preliminary evaluation and analysis of cold weather composting. Although it may not be appropriate to directly transfer all the conditions used in municipal or industrial waste composting to systems designed for hazardous waste composting, a great deal of knowledge can be obtained from previous research information on composting municipal and industrial solid wastes. Hence, the parameters that affect composting in warm and temperate environments also influence composting in cold climates.

For instance, a combined effect of temperature, moisture content and aeration or heat circulation can have very significant impact on the success or failure of composting operation in a cold environment. Moreover, the interactions among these factors on the microbial activity and the nature and stability of biotransformation products will ultimately determine the time required for acceptable composting to occur. Hence, these four factors in addition to those previously discussed have to be carefully evaluated in the engineering design of cold weather composting.

EVALUATION OF LOUISIANA ARMY AMMUNITION PLANT COMPOST DESIGN AND STRUCTURAL INTEGRITY FOR COLD CLIMATES

As noted previously, Williams et al. (1988) have successfully conducted a field demonstration for the composting of explosives-contaminated sediments at the Louisiana Army Ammunition Plant (LAAP). The LAAP static compost pile was designed large enough to be a self-sustaining compost pile. For a full-scale remediation action, piles of greater dimensions than the LAAP compost pile would probably be used. It has been proposed that such piles would generally be 2–3 times as high and wide and about 100–200 ft long. However, at the time when this report was prepared, the LAAP compost pile was the first and only field demonstration compost pile for explosives-contaminated soils in a warm environment available for evaluation for use in cold climates.

A second field test has since been conducted at the Badger Army Ammunition Plant (BAAP) in Baraboo, Wisconsin, to compost propellant-contaminated soil. The same design and construction methods for the LAAP compost project were used for the BAAP project. The following describes an evaluation of the design and structural integrity of the LAAP compost pile for use in cold climates.

Structural valuation

A cross-sectional schematic view of the LAAP compost pile with the structural frame and corrugated tin roof is shown in Figure 12. During the visit to the Badger Army Ammunition Plant by Dr. O. A. Ayorinde and Dr. C.M. Reynolds of CRREL in January 1989, Dr. R.T. Williams of Roy F. Weston, Inc., stated that the compost system design for the BAAP composting project was similar to that used at LAAP.

According to Steve Harman of BAAP, the only difference was that a wood roof supported by 6- × 6-in. wood columns was used at BAAP, whereas, at LAAP, a steel roof supported by steel wide-flange (W8 × 28) columns was used. In addition, the roof angle was 5° (1- to 12-in. slope) for the LAAP roof design and 18.5° (4- to 12-in. slope) for the BAAP roof design.

Roof analysis

Roof structures are usually designed to carry dead and snow loads, especially in cold and snowy environments. A typical design dead load for corrugated tin-plated steel roof is 2 lb/ft² (psf). This value is true whether the roof is made up of steel or wood trusses and braces. The recommended design snow load for the northern Great Lakes area and New England is 40–50

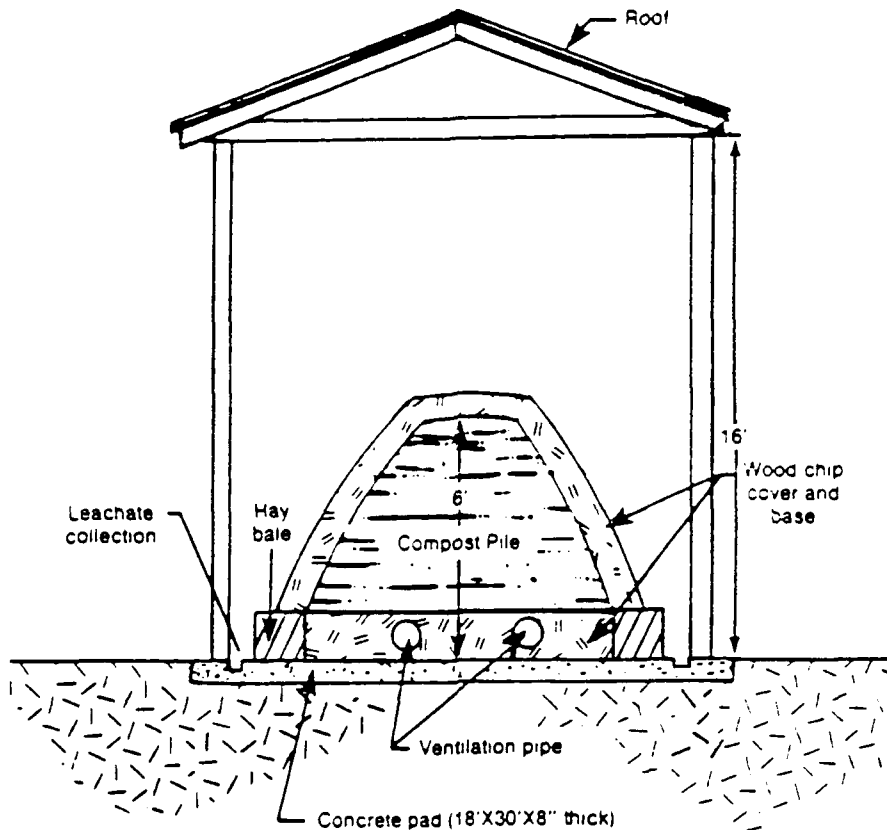


Figure 12. Cross-sectional schematic (not to scale) of compost pile with roof, Louisiana Army Ammunition Plant (Williams et al. 1988).

psf (Merritt 1976). Assuming that the LAAP compost pile roof design had adequate trusses and braces that were properly spaced, welded and connected for rigidity, the roof can safely withstand the combined dead and snow load projected for cold climates. This assessment is based on the following analysis.

Suppose laminated southern pine was used for constructing the LAAP compost system. The allowable fiber stresses and strength are given as follows (American Institute of Timber Construction 1974):

Compressive stress parallel to grain
= 1500 psi

Compressive stress perpendicular to grain
= 385–450 psi

Tensile stress parallel to grain
= 1600 psi

Bending stress of extreme fiber
= 1800–2600 psi

Horizontal shear
= 200 psi

Modulus of elasticity
= $1.6\text{--}1.8 \times 10^6$ psi

where psi = pounds per square inch of surface area.

The load direction and relation to grain of wood is given by the Hankinson formula:

$$N = \frac{PQ}{P \sin^2\theta + Q \cos^2\theta} \quad (14)$$

where N = allowable stress induced by load acting at an angle to the grain direction (psi)

P = allowable stress parallel to the grain (psi)

Q = allowable stress perpendicular to the grain (psi)

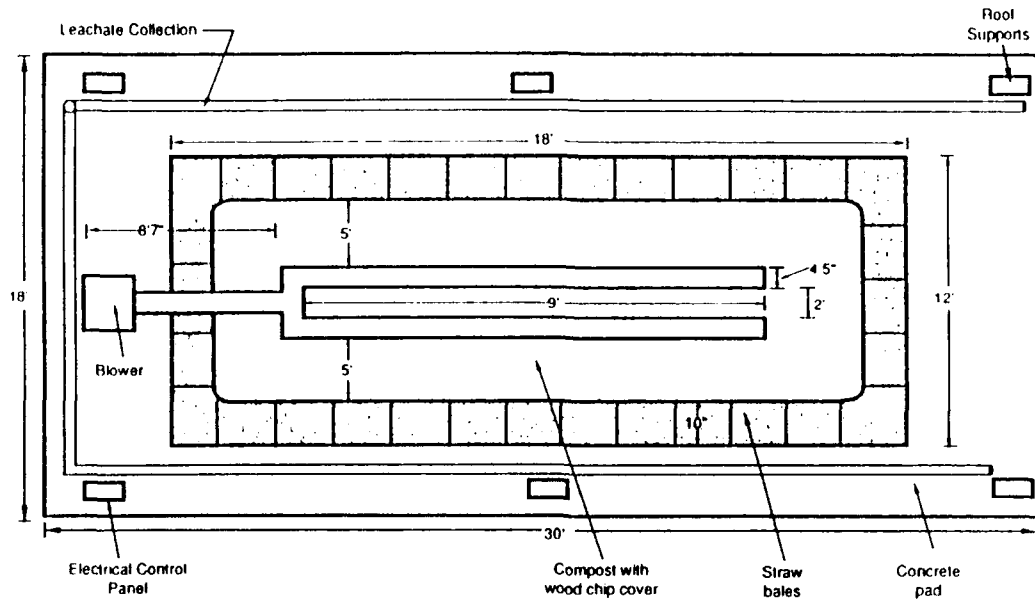
θ = angle between the direction of load and the direction of grain (degrees).

For a steel roof, assuming a carbon steel with a yield strength (F_y) of 36,000 psi and using the American Institute of Steel Construction (AISC) Code (1973), the allowable stresses are given as follows:

Axial stress, $F_a = 0.60F_y = 21,600$ psi

Shear stress, $F_v = 0.40F_y = 14,400$ psi

Bending stress, $F_b = 0.66F_y = 23,760$ psi



Note: Schematic only, not to scale

Figure 13. Overview schematic diagram of compost pile, Louisiana Army Ammunition Plant (Williams et al. 1988).

From the plan view of the LAAP compost pile structure given in Figure 13, the plan area assumed covered by the roof is about 30 ft \times 18 ft, which is equal to 540-ft² area. Hence, total dead and snow load assumed to be carried by the roof (neglecting wind load, etc.) is given by

$$\text{Total roof load} = 540 \times (2 + 50) = 28,080 \text{ lbf.}$$

But the cross-sectional area (A) of W8 \times 28 steel member is 8.23 in.². Hence

$$\begin{aligned} \text{Allowable axial load} &= 21,600 \times 8.23 = 177,768 \text{ lbf} \\ \text{Allowable shear load} &= 14,400 \times 8.23 = 118,512 \text{ lbf} \\ \text{Allowable bending load} &= 3,760 \times 8.23 = 195,545 \text{ lbf.} \end{aligned}$$

Therefore, any of the roof members, whether in bending, shear or compression, will be more than adequate to withstand the dead and snow loads, with more reserved strength to withstand additional wind load.

Roof alone inadequate protection against wind-aided snow and rain

According to Williams et al. (1988), the corrugated tin roof was supposed to provide an adequate protection from precipitation for the LAAP compost pile. Since the composting test pads were covered with an open-sided frame structure, the roof alone cannot provide adequate protection against wind-aided snow and rain caused primarily by high cross winds intruding and wetting the compost pile. To avoid this problem, the sides of the

frame structure need to be closed and an appropriate design made to include wind load.

Columns

Because CRREL did not have access to the actual design and structural drawings and details of the LAAP compost pile design system at the time of this analysis, it was assumed that the columns were made of W8 \times 28 steel with $F_y = 36,000$ psi.

The height of each column to the eave of the roof is 16 ft (see Fig. 12). Using the American Institute of Steel Construction (AISC) Code (1973) for column design with the assumption that the column effective length with respect to its major axis is 16 ft, then the allowable axial load is given as

$$\begin{aligned} \text{Each column axial allowable load} &= 86,000 \text{ lbf} \\ \text{Total column axial allowable load} &= 86,000 \times 6 \\ &= 516,000 \text{ lbf} \end{aligned}$$

Compared to the total roof load of 28,080 lbf which is transmitted to the six column supports, it can be seen that the columns have over 18 times carrying capacity (516,000 lbf). Hence, the columns are structurally adequate.

Thermal performance evaluation

For an analytical evaluation of the thermal performance of the wood chips used as insulating covers for the compost pile (see Fig. 12), the thermal conductivity

values of the wood material and their dependence on the moisture content must be known. Also, concrete thermal properties are needed.

The heat flow rate per unit area through the flat bottom of the pile is given by (Kreith 1958)

$$q/A = U(T_i - T_o) \quad (15)$$

$$U = 1/(t_w/k_w + t_c/k_c) \quad (16)$$

where q/A = heat flow rate per unit area (Btu/hr-ft²)

t_w, t_c = thickness of the bottom wood chip and concrete, respectively (in.)

k_w, k_c = thermal conductivity of wood and concrete, respectively (Btu/ft²-in. °F)

T_i = inner surface temperature of the wood chip (°F)

T_o = outer surface temperature of the concrete (°F).

During winter, eq 15 indicates that there would be a heat loss since $T_i > T_o$ when the compost process is still active.

Assuming the surface of the top wood chip cover for the compost pile is semi-circular in shape, then the conductive heat flow per unit area through the top wood chip cover is given by

$$q/A_g = k_w(T_o - T_i)/(r_o - r_i) \quad (17)$$

$$A_g = (A_o - A_i)/\ln(r_o/r_i) \quad (18)$$

where A_g = logarithmic mean area (ft²)

A_o, A_i = outer and inner surface areas, respectively (ft²)

r_o, r_i = outer and inner radii, respectively (in.).

The total heat loss can be estimated by the following equation:

$$Q = (U_{bm}A_{bm} + (k_w A_g/(r_o - r_i)) + U_{top}A_o) \times (T_i - T_o) \quad (19)$$

where Q = total rate of heat loss (Btu/hr)

A_{bm} = bottom surface area (ft²)

U_{bm} = overall heat transfer coefficient between the bottom surface and the surrounding (Btu/hr-ft²-°F)

U_{top} = overall heat transfer coefficient between the top surface and the surrounding (Btu/hr-ft²-°F).

The thermal conductivity values for different types of wood (oven dry, across grain) at 85°F vary from 0.41

Btu/hr-ft²-in.-°F for balsa to 1.19 for red oak. The average value is about 0.80 Btu/hr-ft²-in.-°F. The value for southern pine yellow wood is about 0.94. The thermal conductivity for concrete is approximately 12.6 Btu/hr-ft²-in.-°F, which is about one order of magnitude more heat conductive than wood (Baumeister et al. 1978).

In general, thermal conductivity for wood is approximately equal in radial and tangential directions, but is about 2^{1/2} times greater along the grain. In addition, thermal conductivity for wood tends to increase with moisture content (American Institute of Timber Construction 1974):

$$k_w = SG \times (1.39 + 0.028 \times MC) + 0.165 \quad (20)$$

where SG is the specific gravity based on volume at current moisture content and oven dry weight, and MC is the moisture content (%). A graphical representation of the effect of moisture content on thermal conductivity is shown in Figure 14.

Based on the thermal conductivity values of wood cited above and how these values can be increased by increasing moisture content given by eq 20, it can be observed from eq 19 that significant heat loss may occur in the winter when there is a large difference between the compost pile temperature and its ambient temperature. Hence, it can be inferred that wood chips alone may not be adequate to provide needed insulation for compost piles in cold climates.

Observations and discussion with the BAAP compost project personnel at Baraboo, Wisconsin, suggested that the removal and handling of frozen soil during compost pile construction would involve significant problems. Hence, handling problems would need to be considered for cold weather composting.

Furthermore, the experience at the BAAP compost pilot field test showed that the thermocouple probe was frozen into the pile in January of 1989, even though the composting was started in the summer months of 1988 and the winter of 1988/1989 was milder than usual. One possible explanation for the frozen thermocouple was that the microbial activity was almost complete with no further heat being generated to counterbalance the cooling effect of the winter cold air temperature. Even then, eq 19 indicates that significant heat loss may occur for a composting process initiated during the winter months in cold regions. Therefore, the LAAP compost pile design may require modification to avoid operational difficulties for use in cold climates.

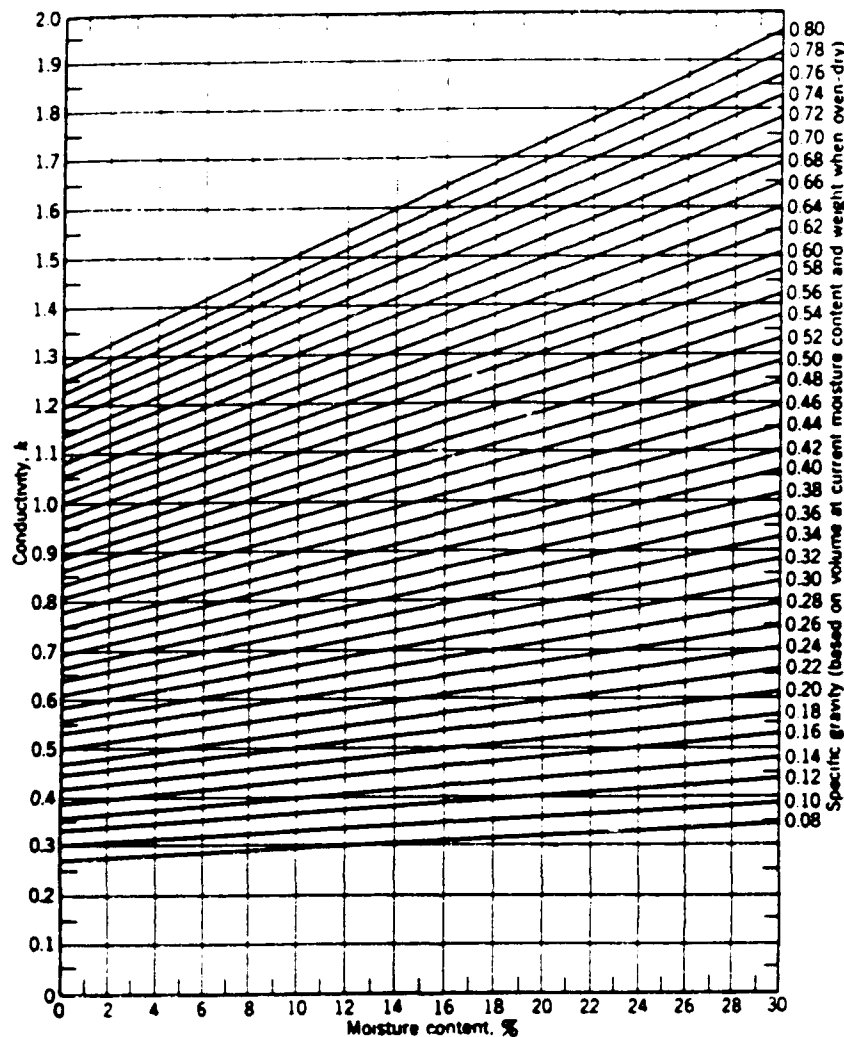


Figure 14. Thermal conductivity values across the grain for wood at various moisture contents and specific gravities (American Institute of Timber Construction 1974).

ANALYSIS OF TEMPERATURE DISTRIBUTION WITHIN A COMPOST PILE IN COLD CLIMATES

From several research studies that have been conducted on composting, there is a general agreement that biological, biochemical and chemical reactions, and the rates of reaction in a composting system are critically dependent on temperature. In fact, as indicated earlier, temperature is the most significant factor influencing the performance of a composting system. Hogan et al. (1989) have shown that, due to the microbial activity, the compost temperature in-

creases rapidly to a maximum (self-limiting value), then drops slightly to a thermophilic level and maintains the temperature before an abrupt decrease to around the mesophilic level. Therefore, it is important to know about the distribution of temperature within the compost generated by microbial activity in a cold environment.

The geometry of the compost pile used to guide this analysis is shown in Figure 12. To simplify the complex geometry of the actual compost pile for mathematical analysis, a semi-cylindrical geometry is assumed as shown in Figure 15. This is, of course, a very crude approximation to make the problem mathematically tractable.

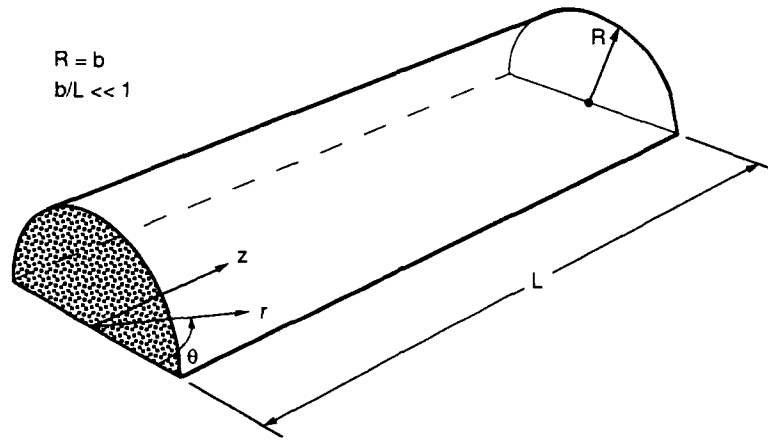


Figure 15. Simplified cylindrical geometry of the compost pile.

Problem formulation

For a nonhomogeneous isotropic composting material, which is not in motion relative to itself, and the pressure and dissipation terms neglected, the general equation of conduction is given by (Carslaw and Jaeger 1959, Rohsenow and Hartnett 1973, Lunardini 1988)

$$\text{div}(\bar{k} \text{ grad } T) + f(x, t) = \rho c_p \frac{\partial T}{\partial t} \quad (21)$$

where x is a position coordinate vector and t is a time variable. In cylindrical coordinates, assuming homogeneity, the general equation is given by

$$\nabla^2 T + \frac{1}{k} f(r, \theta, z, t) = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (22)$$

where r, θ, z = cylindrical coordinates

$$\nabla^2 = \text{Laplacian} = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}$$

T = compost temperature

k = compost thermal conductivity

$\alpha = k/\rho c_p$ = compost thermal diffusivity

ρ = density

c_p = specific heat at constant pressure

f = heat generated or produced within the compost per unit volume per unit time.

Different forms of heat production function for composting materials

It has been shown by Haug (1980), MacGregor et al. (1981), Strom (1985), Finstein et al. (1986a,b) and

Williams et al. (1988) that, above mesophilic and within thermophilic temperature ranges, there is a faster microbial activity leading to a rapid generation of heat within a composting material. Some of the different forms of the heat production functions used by Ayorinde et al. (1990) are described below.

When heat is produced by a zero-order chemical reaction, the rate of heat production can be represented by the Arrhenius equation in the form of

$$f = A_0 \exp(-m/T) \quad (24)$$

where A_0 and m are constants, and T is the absolute temperature. Lomax et al. (1984), in their computer simulation model of mushroom compost heat production, assumed that the amount of dry matter in the compost could be used as the independent variable for calculating heat production. Thus

$$Q_b = E_d M_d \times 5.12 \times 10^4 \exp[-5900/(T_b - 273)] \quad (25)$$

where Q_b = heat production of bed (W/m^2)

E_d = heat energy in dry matter (kJ/kg)

M_d = dry matter per square meter (kg/m^2 of bed)

T_b = average temperature of bed ($^\circ\text{C}$).

Equation 25 is a special form of eq 24. Using either eq 24 or 25 in eq 22 results in an equation for which there is no analytical exact solution. It can only be solved by numerical method.

In addition to chemical reaction, heat may be produced in a solid material by a) the passage of electric

current, b) dielectric or induction heating, c) radioactive decay, d) absorption from radiation, and e) mechanical generation in viscous or plastic flow. In all these cases, the rate of heat production can be approximated as

$$f = a + bT \quad (26)$$

where a and b are constants which may have either sign. For a composting material where heat production is caused primarily by biochemical reaction, eq 26 can be used as a crude first approximation, since eq 22 can be solved exactly when the form of f in eq 26) is used and T is a function of r only.

Cases to be considered include:

a) *Steady-state solution*. This approximates conditions when a compost pile temporarily is at a stable thermophilic temperature after reaching the self-limiting condition.

b) *Non-steady-state solution*: This approximates conditions when the compost pile starts microbial activity at a mesophilic or thermophilic constant initial temperature.

Basic assumptions made for the analysis

1. The compost pile is cylindrical in shape.
2. Composting material is homogeneous and isotropic with constant thermal conductivity at a given state of moisture content. The thermal conductivity may change as the moisture content of the composting material varies with time.
3. Composting material is also axisymmetrically uniform so that its temperature distribution varies only with radius, i.e., in the r direction only.
4. Compost pile diameter-to-length ratio is small, i.e., $d/L \ll 1$.
5. Temperature change within the compost pile is primarily caused by heat conduction.
6. The net radiant energy conducted into the composting is negligible.

Steady-state solution and its assumptions

In addition to the above general assumptions, the following assumptions are made:

1. Rate of heat generation due to microbial activity is constant.
2. Mean annual ambient temperatures are fixed in value.
3. Temperature distribution is only a function of the compost pile radius and not of time.
4. Surface heat loss is both free and forced convection.

Assuming a constant heat generation rate, A_0 , eq 22 becomes

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{dT}{dr} \right) + \frac{A_0}{k} = 0 \quad (27)$$

Boundary conditions:

$$\text{At } r = b; \text{ outer surface, } k \frac{dT}{dr} + h(T - T_{\text{out}}) = 0 \quad (28)$$

At $r = 0$, $T(r)$ is finite.

The steady-state solution is given by

$$T(r) = (A_0 b^2 / 4k)(1 - r^2 / b^2) + (A_0 b / 2h) + T_{\text{out}} \quad (29)$$

where b = outer radius

h = surface heat transfer coefficient

T_{out} = ambient air temperature or temperature of the medium surrounding the compost pile.

T_{out} can only be a constant for a steady-state solution. For non-steady-state solutions, T_{out} can be a linear function or sinusoidal function of time.

Rearranging and normalizing with respect to the Biot Number (B_i), eq 29, becomes

$$[T(r) - T_{\text{out}}] / B_i = (A_0 b / 4h)(1 - r^2 / b^2) + (A_0 k / 2h^2) \quad (30)$$

where $B_i = hb/k$.

Table 3 shows the values of A_0 used for the analysis. They are based on the maximum rates of heat production for various composting materials obtained from the literature. The values of T_{out} used for calculation represent the mean of the maximum and minimum tem-

Table 3. A_0 values. Maximum rates of heat production for various materials.

| Composting material | Heat liberation rate (watts/kg dry matter) | Reference |
|---------------------|--|----------------------------|
| Municipal refuse | 21.2 | Wiley (1957) |
| Oat straw | 12.5 | Carlyle and Norman (1941) |
| Wool | 5.0 | Walker and Harrison (1960) |
| Gin trash 77 | 20.0 | Griffis and Mote (1982) |
| Gin trash 78 | 28.0 | Griffis and Mote (1982) |
| Dairy manure | | |
| Rice hulls | 27.0 | Griffis and Mote (1982) |

Table 4. T_{out} values.

| Location | Temperature ($^{\circ}\text{C}$) | | Time period | Reference |
|-----------------|------------------------------------|------|----------------|------------------|
| | Min. | Max. | | |
| Bangor, Me. | -17 | -17 | Winter 1977 | Finstein (1986b) |
| Baraboo, Wis. | -29 | 38 | Winter 1986-87 | CRREL |
| Shreveport, La. | -12 | 20 | Winter 1986-88 | CRREL |

peratures obtained for Shreveport, Louisiana, Baraboo, Wisconsin, and Bangor, Maine, as shown in Table 4. The k and h values used are depicted in Tables 5 and 6, respectively. Figures 16 and 17 depict the effects of the changes in the ambient temperature (T_{out}) on the steady-state compost temperature distribution predicted by eq 29 for $H = 1$ and $H = 50$, respectively. Because of the assumptions imposed on the steady state solution, increasing the surface heat transfer coefficient from 1 to 50 shows relatively no change on the normalized compost temperature distribution. However, significant changes occur when, at a given surface heat transfer coefficient, the ambient temperature is varied from 0°C to -29°C .

Non-steady state solution and its assumptions

For the non-steady-state solution, the heat generating function was used implicitly rather than explicitly as done for the steady-state solution. This is based on the assumption that the microbial activity within the compost pile has reached its optimum level, and the self-limiting or thermophilic temperature range has been attained and maintained for a period of time (MacGregor et al. 1981).

In addition to the above general assumptions, the following assumptions are made:

1. Initial temperature is constant within the thermophilic temperature range.
2. Compost pile surface is maintained at a constant temperature equal to the ambient temperature.
3. Temperature within the compost pile is a function of time and pile radius.

For initial temperature T_o and surface temperature maintained at T_s , the non-steady state form of eq 22 becomes

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} = \frac{1}{\alpha} \frac{\partial T}{\partial t}, \quad 0 < r < b. \quad (31)$$

Boundary condition: $T = T_s$ at $r = b, T > 0$
Initial condition: $T = T_o$ when $t = 0$

Solution is given by:

$$\frac{T(r) - T_o}{T_{out} - T_o} = 1 - 2 \sum_{n=1}^{\infty} \exp(-\beta_n^2 \tau) \frac{J_0(r\beta_n/b)}{\beta_n J_1(\beta_n)} \quad (32)$$

where

$$\beta_n = b\gamma_n \quad (33)$$

$$\tau = \alpha t/b^2. \quad (34)$$

Equation 32 is plotted in Figure 18 with $T_{out} = T_s$ as a function of normalized radius, r/b , b being the outer radius of the compost pile. From eq 34 and Figure 18, it is possible to estimate how long it will take for the fall in compost temperature below its initial temperature to reach 95% of the ambient temperature. Hence, for $[T(r) - T_o]/(T_s - T_o) = 0.95$, $\tau = 0.4$. Thus, from eq 34,

$$t = (0.4 \times b^2)/\alpha \quad (35)$$

Table 6. $H = h/k$ values.

| h ($\text{cal/cm-s-}^{\circ}\text{C}$) | k ($\text{cal/cm-s-}^{\circ}\text{C}$) | H (cm^{-1}) |
|---|---|-----------------------------|
| 9.37×10^{-4} | 0.18×10^{-4} | 52.0 |
| | 0.90×10^{-4} | 10.4 |
| | 0.62×10^{-3} | 1.51 |
| | 1.5×10^{-3} | 0.62 |
| | 2.1×10^{-3} | 0.45 |
| | 5.6×10^{-4} | 1.67 |
| | 1.1×10^{-3} | 0.85 |

Table 5. k values.

| Composting material | k ($\text{cal/s-cm-}^{\circ}\text{C}$) | Reference |
|-----------------------|---|--|
| Sewage sludge | $0.62-2.1 \times 10^{-3}$ | Hogan et al. (1989) |
| Wood | $0.90-6.7 \times 10^{-4}$ | American Institute of Timber Construction (1974) |
| Swine waste and straw | $0.56-1.1 \times 10^{-3}$ | Mears et al. (1975) |

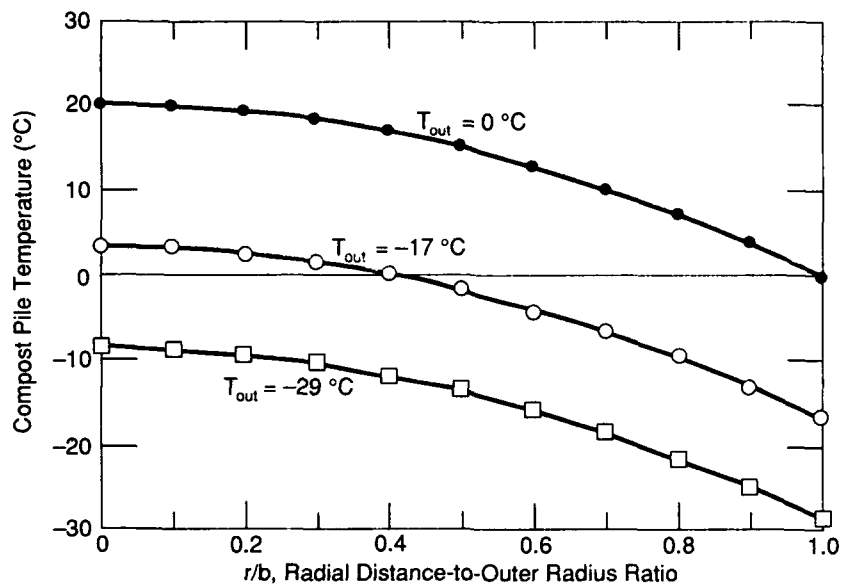


Figure 16. Steady-state solution for compost pile with constant heat production rate, $H = 1$.

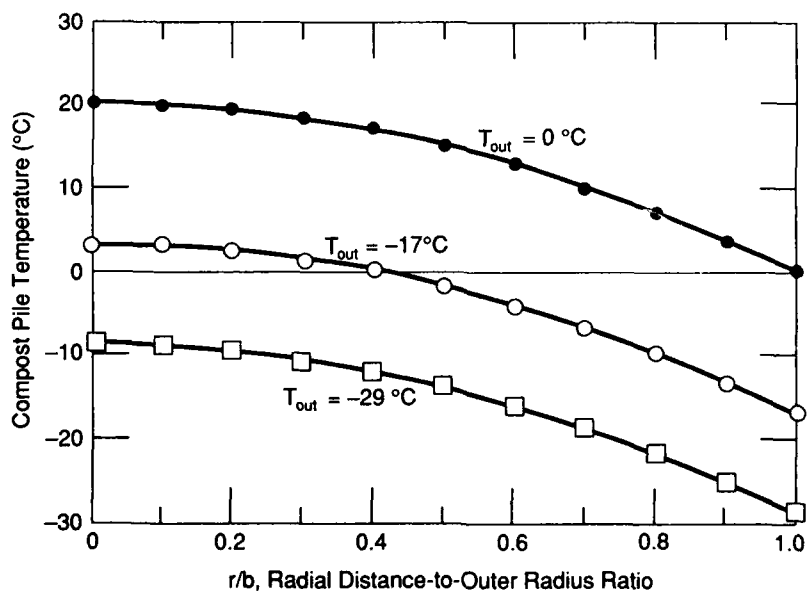


Figure 17. Steady-state solution for compost pile with constant heat production rate, $H = 50$.

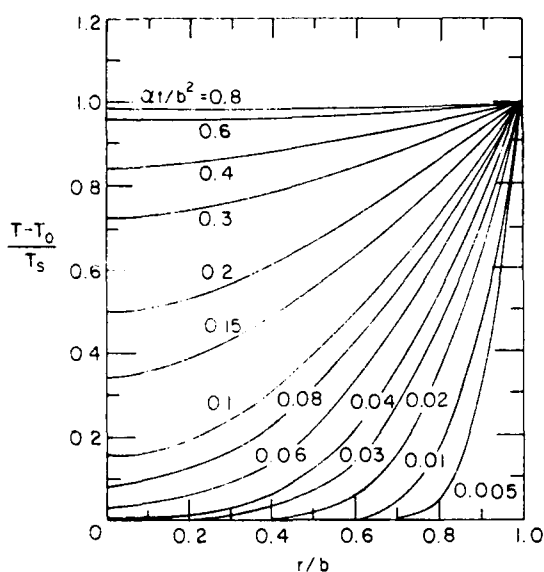


Figure 18. Transient temperature distribution for a compost pile with a surface temperature, T_s (Carslaw and Jaeger 1959).

CONCLUSIONS AND RECOMMENDATIONS

1. A thorough review of available literature was conducted on the impact of cold climates on composting, with emphasis on composting explosives, the influence of engineering design on compost pile temperatures, and the control and measurement of compost pile temperatures.

2. It was found that there is no universal definition of composting. In a broad sense, composting has been defined as the biological decomposition (involving biodegradation and biotransformation processes) of organic substrates under conditions that allow development of mesophilic temperatures (with an average of 35°C) and thermophilic temperatures (with an average of 55°C) as a result of biologically produced heat, with a final product sufficiently stable for storage and application to land without adverse environmental effects.

3. The majority of published research on composting has been focused on the composting of municipal and industrial solid wastes. It is important to realize that the goals of municipal and industrial waste composting differ from the goals of hazardous waste composting. The desired goal must be considered when adapting municipal waste composting techniques to hazardous waste composting.

4. To date, no research information or data are found in the literature on the sustained effect of a cold climate on composting.

5. Although it may not be appropriate to directly transfer all the conditions used in municipal or industrial waste composting to systems designed for hazardous waste composting, a great deal of knowledge can be obtained from research information on the composting of municipal and industrial solid wastes.

6. Parameters that consistently have been found to significantly influence composting include temperature, moisture content, and chemical and biological characteristics, as well as the concentrations of the organic substrates, the concentration of available nutrients such as nitrogen and phosphorus, the ratio of available nutrients such as organic carbon and nitrogen (C/N), heat production and retention in the compost, and the partial pressure of oxygen within the compost material.

7. There is little information available on the persistence and fate of intermediate metabolites formed during composting of explosives. Because some metabolites are known to be toxic, this question needs to be resolved before composting can be used for decontaminating explosives-laden soils and sediments. Nevertheless, due to the self-heating nature of the composting process, the ability to design composting systems in which optimum temperatures can be maintained, and the likelihood that some hazardous materials may be rendered harmless permanently by incubation under appropriate conditions, composting may offer an attractive decontamination method that is well suited for cold regions use.

8. Both the roof and the columns for LAAP compost pile are structurally adequate to withstand dead, snow and wind loads that may be encountered in a cold environment.

9. Since the LAAP composting test pads were covered with an open-sided frame structure, the roof alone cannot provide adequate protection against snow and rain with high cross winds intruding and wetting the compost pile. To avoid this problem, the sides of the frame structure need to be closed and an appropriate design made to include wind load. For future full-scale compost piles for field remediation of explosives-contaminated soils, an in-vessel compost system is recommended.

10. The experience at the BAAP compost pilot field test suggests that significant heat loss can be expected for a composting process initiated during the winter months in cold regions, even though the composting was started in the summer months of 1988 and the winter of 1988–1989 was relatively milder than usual. Also there were potential soil handling problems during winter period. Therefore, the LAAP compost pile design may require modification to avoid operational difficulties for use in cold climates.

11. For the steady-state solution, it was found that a) for a given rate of microbially produced heat, temperature distribution within the compost is significantly influenced by low ambient temperature, b) surface heat loss is the same for both free and forced convection (this is as a result of the crude assumption of no dependence on time), and c) temperature decreases nonlinearly from the center of the compost pile to its outer surface.

12. For the non-steady-state solution, it was established that a) the compost temperature change above its initial temperature is strongly dependent on its surface temperature and thermal diffusivity, and b) time for the compost temperature change to reach a prescribed percentage of the surface temperature is directly proportional to the square of the radius of the compost pile and inversely proportional to its diffusivity.

13. Since no thermal properties (e.g., thermal conductivity, thermal diffusivity, etc.) for the LAAP and BAAP compost piles were available at the time the analysis in this report was performed, no comparison between the analytically predicted temperatures and field-measured temperatures was done. Hence, it is recommended that a follow-up laboratory measurement of the thermal properties of frozen and unfrozen compost pile material should be performed. To properly model the compost pile for comparison with the field temperature measurements, a finite element analysis involving an elaborate computer code is recommended.

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